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**Cockpit Displays to Support Hazard
Awareness in Free Flight**

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Cockpit Displays to Support Hazard Awareness in Free Flight

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Abstract

Three experiments are described which each examine different aspects of the formatting and integration of cockpit displays of traffic information to support pilots in traffic avoidance planning.

The first two experiments compared two-dimensional (coplanar) with three-dimensional (perspective) versions of a cockpit display of traffic information. In Experiment 1, 30 certified flight instructors flew a series of traffic conflict detection and avoidance maneuvers around an intruder aircraft, sometimes in the presence of a second intruder. The results revealed an advantage for the coplanar display, particularly when there was vertical intruder behavior. In Experiment 2, 17 instructors flew with the coplanar and perspective formats when weather information was either overlaid or displayed separately. Again performance was best with the coplanar display, particularly when the weather data were overlaid. The results of both experiments are also discussed in terms of the traffic maneuver stereotypes exhibited by the pilots.

Experiment 3 examined the benefits of the two different predictor elements used in the coplanar displays of Experiments 1 and 2. The study was carried out in a multitask context. These elements were both found to improve safety (reduce actual and predicted conflicts) and to reduce workload, although the different elements affected workload in different ways. Neither predictor element imposed a cost to concurrent task performance.

Introduction

Advances in computer graphics, digital communications, and satellite-based navigational systems have fostered a gradual evolution toward better and more refined cockpit traffic displays. In particular the TCAS status display (Chappell, 1990), has undergone gradual refinement, has in some aircraft become integrated with the high resolution Horizontal Situation Indicator, and is now being evaluated for use in some actual navigational tasks (e.g., in-trail climb in oceanic flight), as well as its more conventional use as a status display for conflict avoidance.

The seeds for the TCAS status display were planted in the work by NASA in the 1970s and 1980s on the Cockpit Display of Traffic Information or CDTI (Abbott et al., 1980; Kreifeldt, 1980; Ellis, McGreevy, & Hitchcock, 1987). Although efforts to provide pilots with traffic displays of a larger region around ownship were terminated because of concerns regarding visual workload and ATC authority, renewed interest has been triggered because of considerations of free flight (Planzer & Jenny, 1995; RTCA, 1995), a concept intended to reallocate some aspects of strategic planning, and tactical conflict avoidance from ATC to the flight deck. However, the development of good traffic displays, based upon GPS capabilities, should be considered an important issue independent of whether free flight procedures are realized.

One issue that we address in this report is the appropriate format that a CDTI should take. Extensive work on CDTI symbology has been carried out (e.g., Hart & Wempe, 1979; Abbott et al., 1980). Importantly, at least one study examined whether the CDTI should be presented in planar (2D) or perspective (3D) format. In this study, Ellis et al. (1987) demonstrated the superiority of the 3D format, and showed that this format encouraged a greater degree of vertical maneuvers in conflict avoidance. However, the 2D format with which it was compared only presented the vertical traffic information symbolically, by a dichotomous code of above/below ownship and by digits. Hence, the 3D display might have realized an advantage because of the more compatible analog information conveyed regarding altitude, rather than because of its perspective view. In the current research program we compare a 3D (perspective) display with a 2D **coplanar** counterpart, which presents the altitude dimension in analog format. As we have argued elsewhere (e.g., Wickens et al, 1996; Olmos et al, 1997a; Olmos et al., 1997b), each format has its own set of strengths and weaknesses.

The concept of free flight has also raised issues concerning "rules of the road." How should aircraft maneuver given basic properties of the conflict geometry: who should climb, descend, etc.? Such rules are built into the complex

algorithms of the TCAS resolution advisory, but for the more flexible, less time constrained maneuvers envisioned in a free flight regime, it is unlikely that decision aids can provide full and adequate guidance. However, such rules of the road can be formulated as procedures, in part, by understanding the current conflict avoidance stereotypes shown by pilots. Thus a second goal of this program of research is to evaluate such stereotypes and, in particular, how they might be influenced by the nature of the display (Ellis et al., 1987). These issues are examined in Experiment 1 (Merwin and Wickens, 1996).

The third issue that we address takes a broader scope. Traffic is only one of three spatially defined hazards that pilots must avoid, the other two being weather and terrain. A possible concern is that separate spatially defined displays may be rendered for each hazard class individually; yet the combined implications of all three databases (or any pairwise combination) may well need to be considered for effective maneuvering and flight path planning. For example, the optimal path to avoid a pending conflict may lead the pilot into hazardous weather. In Experiment 2 (O'Brien and Wickens, 1997), we ask whether weather information is best represented as an integrated overlay with traffic, or as a spatially separated database, the advantage for the latter reflected in the lower level of clutter for each information source. We ask this question twice, once with a coplanar display and once with a perspective display. The reason for this duplication is to try to replicate the findings regarding dimensional integration of Experiment 2, and to determine if the costs (or benefits) of dimensional integration are amplified or diminished by the integration of weather and traffic databases.

The final issue that we address concerns the visual workload implications of the CDTI. A display or display feature may prove very effective for its intended task (here, traffic avoidance) but because it is either very compelling, or contains a lot of complex information, it may impose such a high workload as to be disruptive of ongoing flight tasks—particularly those time critical visual tasks involved in out-the-window traffic monitoring. We consider this issue in Experiment 3 (Wickens and Morphew, 1997).

Experiment 1: Display Dimensionality

In Experiment 1, 30 pilots, all certified flight instructors, flew a series of conflict avoidance maneuvers with one of three display types. A coplanar display (Figure 1a) presented a plan view above, and a profile view below, the latter represented from a viewpoint behind ownship. On any given trial, there was a 67% chance that the "intruder" traffic would penetrate the **protected zone** around ownship (5 miles, 1000 ft) if an avoidance maneuver was not

undertaken. The conflict geometry involved a random mix of intruder overtaking, crossing or approaching, from the left or right, and climbing, descending or level. Each pilot participated in two sessions. During the first session only a single intruder was present. During the second session, a second traffic intruder was present. The second intruder was not initially on a conflict course, but maneuvers around the primary intruder needed to consider the geometry of the second. Airspeed was fixed, but pilots could control heading and altitude through conventional flight dynamics.

In the display (Figure 1), predictor vectors on all traffic portrayed a 45 second predictor span. A **threat vector** extended from ownship's predictor in the direction of the intruder at the anticipated time of closest passage (Figure 1a). The length of this threat vector was equal to the size of the protected zone. Thus, if the threat vector touched the intruder's predictor line, this event signaled that ownship was **projected** to penetrate the protected zone of the traffic in the near future. This condition was highlighted on the display by a change in coloration of the symbology, and was designated as a **predicted conflict**. An actual loss of separation resulted when the threat vector of ownship touched the traffic. The position of the intersection of the threat vector with ownship predictor depicted the time remaining till the anticipated point of closest passage. Thus, the vector moved down the predictor line toward ownship, as the point of closest passage (or loss of separation) approach. These features of predictive information were designed to adhere to principles of ecological interface design (Vicente and Rasmussen, 1992), by making perceptual, task relevant variables that might otherwise need to be derived cognitively. The efficacy of these features is examined in Experiment 3.

Identical symbology (predictor and threat vectors) was replicated on the lateral and vertical views of the coplanar display. The perspective (3D) display (Figure 1b) presented analogous symbology, but integrated this into a single view, placing aircraft atop "droplines" to a common base altitude (Ellis et al., 1987). Two renderings of the perspective display were considered; with a 30° and with a 60° elevation angle.

Pilots were cautioned to fly as directly as possible to a waypoint, located on the far side of the traffic at 10,000 feet, but to avoid creating actual or predicted conflicts. In a free flight regime, the latter event for example might signal the required intervention by ATC, a circumstance which would defeat the purpose of free flight.

Results and Discussion: Experiment 1

Full results of Experiment 1 are described in Merwin and Wickens (1996). In the current writing we highlight the most important significant differences.

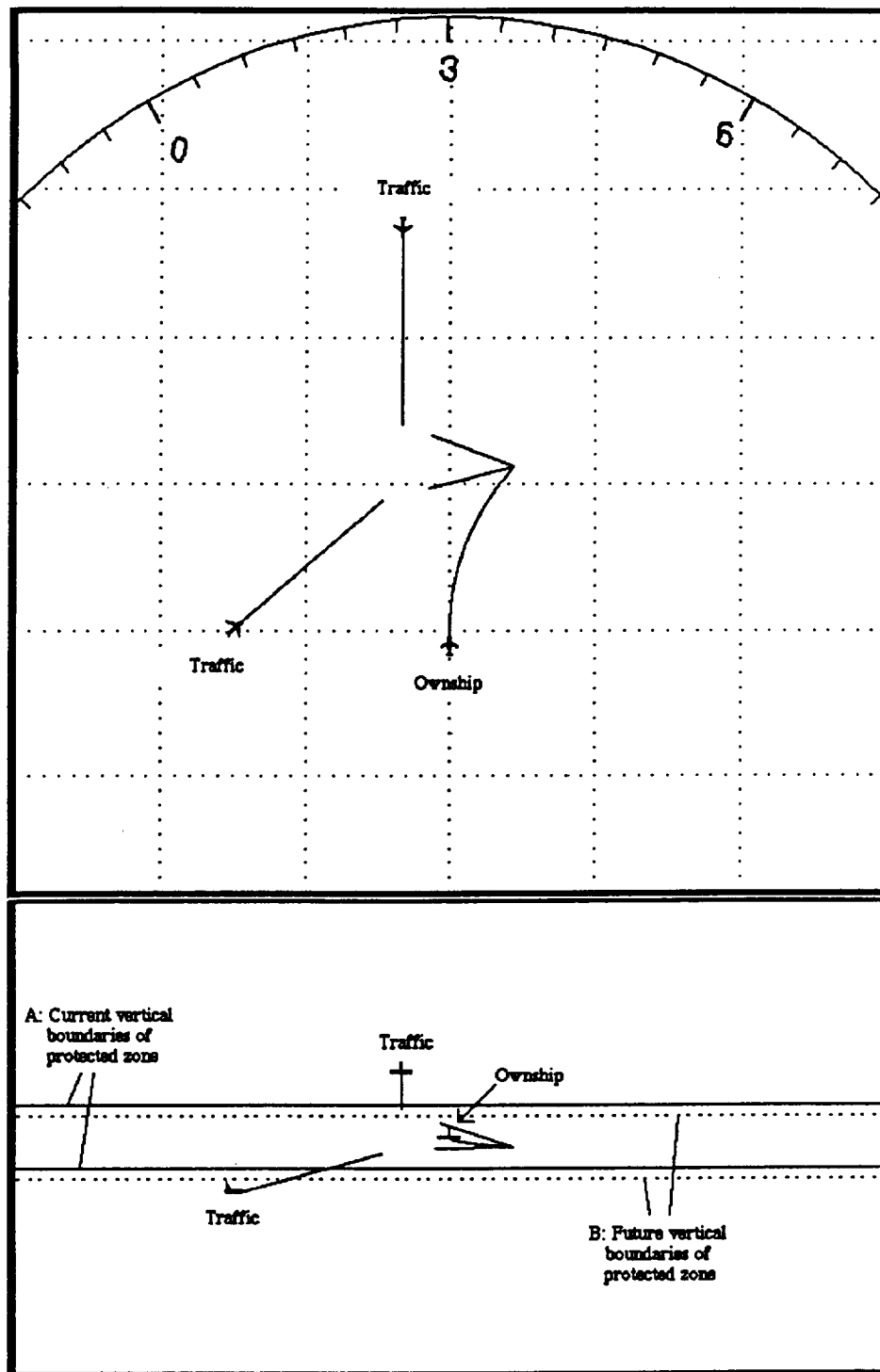


Figure 1a. Depiction of the coplanar display format. The top panel shows a top-down view and the bottom panel represents a view from behind ownship (both panels are orthogonal projections). Each of the displays used in the study had a black background with colored lines used for symbology (see text). These augmentations relieve the pilot of having to estimate the relative altitude difference between other traffic and ownship's current and predicted positions, and offer comparable altitude information to the perceptual enhancements contained in the perspective display described below.

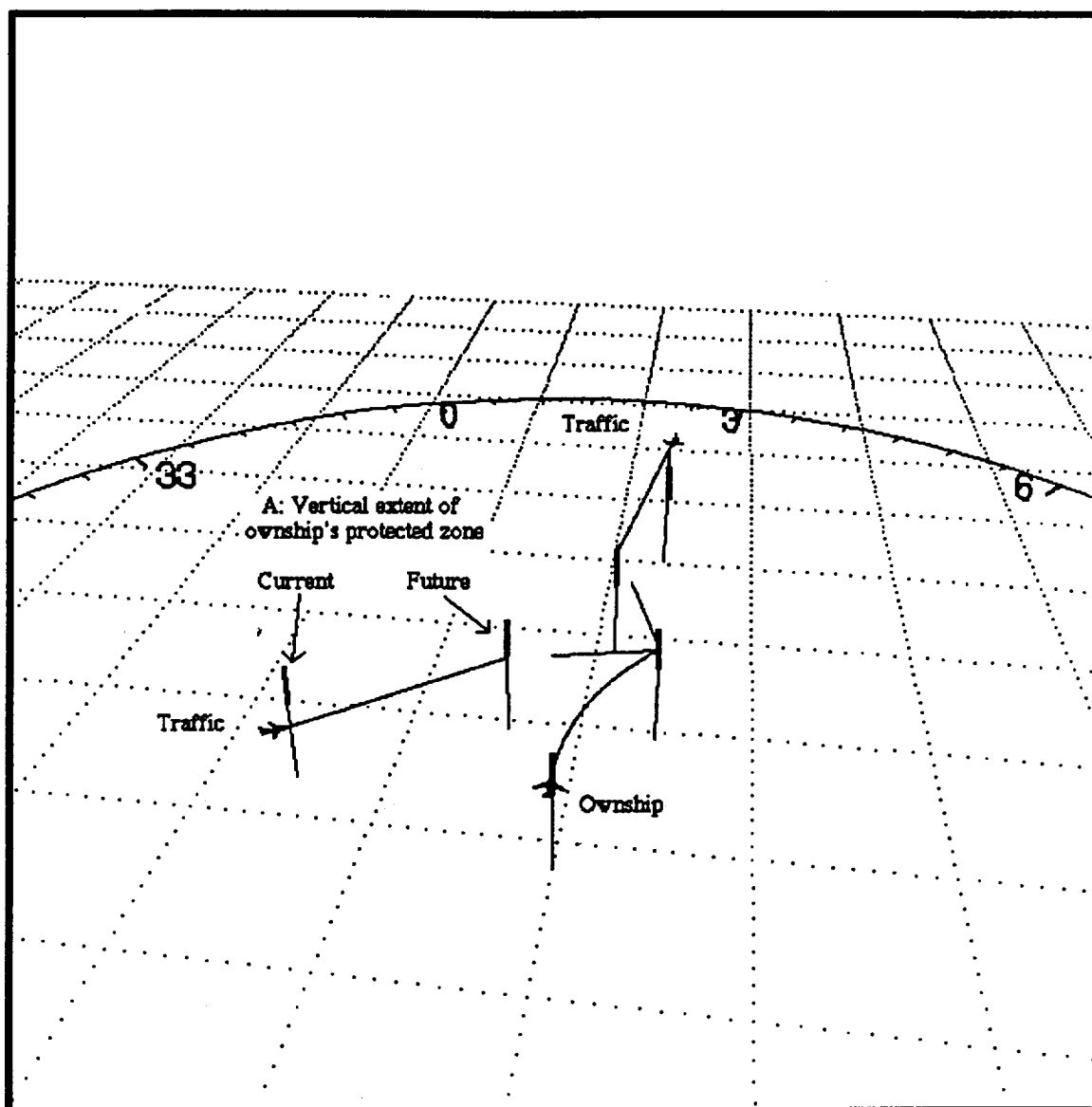


Figure 1b. Depiction of the perspective display format with a 30 ° elevation viewing angle. The thicker line segments on the vertical reference lines indicating the vertical extent of ownship's protected zone are provided for explanatory purposes. On the displays used in the study, these line segments were color coded and were the same thickness as the rest of the reference line.

Flight safety. The results generally indicated that the coplanar display supported safer conflict resolution. Pilots flying with this display showed fewer **predicted** conflicts with the primary traffic ($F_{2,27}=3.06$; $p<.06$), and fewer **actual** conflicts with the secondary traffic ($F_{2,27}=6.55$; $p<.01$) (see Table 1). An important characteristic of the latter differences is that the greater conflict rate for pilots with the perspective display was only shown when the primary traffic was non-level (descending or ascending), a more difficult perceptual problem. Differences between the 30° and 60° perspectives are discussed in Merwin and Wickens (1996).

Table 1

		Coplanar	Perspective	
<u>Primary Traffic</u>	Predicted Conflicts	56%	60°	30°
			70%	83%
<u>Second Traffic</u>	Total	6%	10%	17%
Actual Conflicts	Level	0%	0%	0%
	Non-Level	8%	13%	24%

The intruder geometry also influenced flight safety. Thus, there were more conflicts when the intruder approached from the left ($F_{1,28}=6.35$; $p<.02$), when the intruder was approaching from the front ($F_{2,27}=3.61$; $p<.04$), and when the intruder would pass ahead, rather than behind ownship ($F_{1,28}= 3.78$; $p= .06$).

Maneuver choice. In general, across all displays and conflict geometries, pilots chose to maneuver vertically more than laterally. This may reflect the fact that control dynamics are of lower order (and hence, easier) in the vertical axis, the fact that vertical maneuvers are the most time efficient (Krozel and Peters, 1997), or the fact that there was no ATC simulation in the current paradigm, freeing pilots from responsibility of obtaining clearance for the necessary change in flight level. The coplanar display tended to enhance the tendency to chose vertical over lateral maneuvers. Also pilots using the coplanar display tended to maneuver vertically in the opposite direction to the traffic's vertical behavior, while those using the perspective displays tended to maneuver in the same direction (climb if the traffic was climbing, descend if it was descending).

Experiment 2: Integration of Weather and Traffic

The results of Experiment 1 tended to show generally better performance with the 2D display, an effect opposite to that found by Ellis et al. (1987). In Experiment 2 we examined display dimensionality again. However, rather than imposing a second intruder, as in Experiment 1, here we imposed a weather hazard that needed to be avoided. Our interest was in the extent to which performance involving this second hazard database benefited from its integrated presentation with the traffic hazard database, and how this benefit (if observed) would be modulated by display dimensionality.

Method: Experiment 2

The general procedures in Experiment 2 were quite similar to those in the second session of Experiment 1. However, in place of the secondary traffic, pilots now encountered a generic **weather hazard** or “no-fly zone,” depicted as a rectangular volume on the display. On some trials the initial trajectory, if uncorrected, would lead the pilot to compromise separation from the traffic. On others it would lead them to penetrate the weather hazard. Furthermore, the latter were broken down in terms of trials in which the most efficient direction of avoidance maneuver (left, right, up, down) would lead pilots **toward** the conflicting traffic, and those in which the logical maneuver would lead them away. We reasoned that the former trials would most benefit from the integrated display of traffic and weather (Wickens & Carswell, 1995).

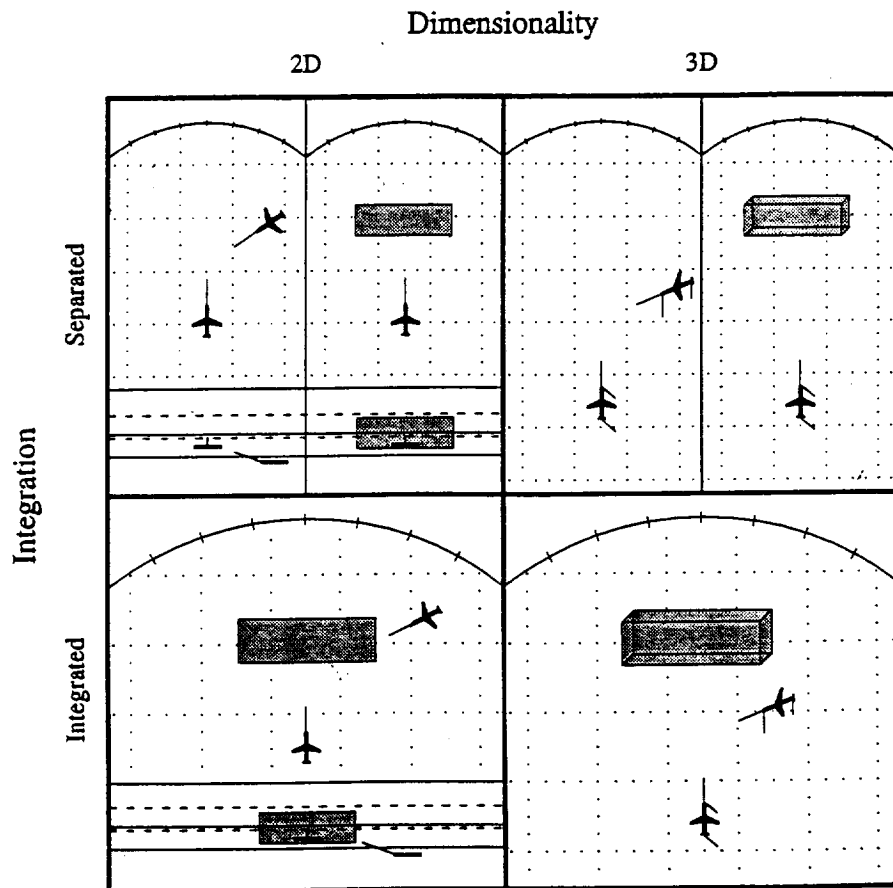
Seventeen instrument-rated pilots each flew a series of 21 conflict trials with all four of the display prototypes, formed by the orthogonal crossing of dimensional integrality (see Figure 1), and database integration. Figure 2 presents a schematic rendering of the four display prototypes.

Results and Discussion: Experiment 2

The effects of dimensional integration generally replicated those of Experiment 1. Measures of flight safety favored the coplanar display, in terms of actual traffic conflicts ($F_{1,16} = 35.74$, $p = .0001$), predicted traffic conflicts, ($F_{1,16} = 47.51$, $p = .0001$) and weather conflicts ($F_{1,16} = 5.42$, $p = .033$). We also observed again, that the loss of performance regarding actual conflicts with the perspective displays was most significant when the traffic was non-level (i.e., climbing or descending).

The effects of database integration were less pronounced, but generally supported the integrated over the separated displays, for both the coplanar and the perspective formats. The benefits of database integration were most

realized on problems in which both weather and traffic were relevant for formulating the solution. For instance, for initial weather hazard trials in which both weather and traffic information were critical for hazard avoidance, the integrated displays resulted in significantly fewer predicted traffic conflicts ($F_{1,16} = 5.65, p = .03$); a benefit that was not observed when the optimum maneuver was away from the traffic. Also, a marginally significant effect of database integration revealed fewer weather conflicts with the integrated displays, for initial traffic hazard trials, where both weather and traffic information must be considered ($F_{1,16} = 4.44, p = .051$).



There was also some suggestion of an interaction between the two display variables, such that the benefits of database integration were enhanced in the coplanar, relative to the perspective format. We infer that this effect results from two opposing influences on performance. On the one hand, the separated coplanar display, presenting four separate display panels may suffer a penalty of excessive visual scanning. On the other, the integrated 3D display, presenting all information within a single panel, may suffer from excessive clutter. Hence, the coplanar integrated format appears to be the optimal display of the four.

Discussion: Experiments 1 and 2

The most prominent finding from the two experiments is the consistent advantage of the coplanar 2D format over the 3D perspective format in supporting traffic avoidance maneuvers. This effect is also consistent with those we have observed earlier in air traffic control (May et al., 1996), and in particular, the enhanced 3D cost observed when non-level traffic is encountered (Wickens et al., 1996b). The data are also consistent with the accuracy costs imposed by the perspective display on pilots judging bearing to terrain features (Wickens et al., 1996a). All of these costs can be attributable to the **ambiguity** with which the perspective display depicts position and separation along the line of sight or the viewing axis of the display. Such ambiguity is not fully resolved by altitude posts (droplines) and grids.

However, it is important to contrast the current findings with two contrary results. First, Ellis et al. (1987) had observed an advantage for the perspective CDTI. However, we noted that the 2D display with which it was compared presented only symbolic and digital representation of the vertical axis, whereas in the current experiments the vertical was represented in linear analog format. This difference may also explain why Ellis et al. found that their 2D (uniplanar) display encouraged LESS vertical maneuvering, whereas the 2D (**coplanar**) display used here encouraged MORE vertical maneuvering.

We may also contrast the current results with the clear benefits of 3D displays that have been reported in studies of flight path guidance (e.g., Haskell & Wickens, 1993; Wickens & Prevett, 1995; Olmos et al., 1997b). The distinction is very important both because the difference in the nature of the task (flight path tracking versus hazard avoidance maneuvering), and the nature of the 3D display **viewpoint**, which was egocentric in the flight path tracking studies, and exocentric here (Wickens, 1997).

Finally, our findings point to the clear advantage of database integration, suggesting that considerable caution should be exercised in adding separate monitors or display units for separate hazard databases. Greater human factors value can be achieved by integrating spatially related databases on a common display, and addressing any clutter issues that may be created as a result, by careful color or intensity coding or decluttering algorithms.

Experiment 3: Workload Implications of Free Flight Displays

The development of the display symbology used for Experiments 1 and 2 had proceeded with consultation and input from experienced pilots. While several had commented favorably about aspects of the symbology shown in Figure 1, some had expressed concern over the amount of clutter presented. Thus, one goal of Experiment 3 was to

systematically compare three display options: a "Baseline" display with only ownship predictor (Fig. 3a), an "Intruder Predictor" display, with predictors on both intruder and ownship (Fig. 3b), and a full "Threat Vector" display which was the same as the coplanar display that had been used in Experiments 1 and 2 (see Figure 3c). The coplanar format was chosen as it had proven best in the first two experiments. A full description of this experiment can be found in Wickens and Morphew (1997).

We were interested in two facets of the two augmentations (the intruder predictor and the threat vector): How well did they support performance in traffic conflict avoidance, and what was the workload imposed by their processing. In particular we hypothesized one of two alternative findings, assuming that each element did indeed improve conflict avoidance performance: (1) Such improvement would be purchased at the cost of added workload and attention demands, because the added information to be processed in the predictor and threat vector imposed an added time cost for its processing. (2) Alternatively, the cognitive engineering principles used to develop these elements, by replacing cognitively loading working memory operations, with more direct perceptual ones, would reduce the resource demands, even as performance improved (Vicente and Rasmussen, 1992). Resource demands were assessed via the NASA TLX workload ratings (Hart and Staveland, 1988). In addition we examined the dual-task resource costs of the three display options, by having our pilots maneuver around conflicts in the presence of a secondary task that mimicked the visual attention demands of head up scanning for visual traffic.

Method: Experiment 3

Fifteen instrument-rated pilots participated in the experiment. Each pilot flew a series of 30 "trials" over a two day period, each trial consisting of an approach to a waypoint, similar to that employed in Experiments 1 and 2. In Experiment 3, nearly all of the trials (7/8) created a conflict with a single intruder. The range of conflict geometries was similar to those employed in the Experiments 1 and 2. All other procedures were similar to the ones used in those experiments except that pilots in the current experiment also had the option of exercising airspeed control in addition to lateral and vertical maneuvering for conflict avoidance, and they were required to perform a secondary task as described below.

During the trials, a very faint light would illuminate at random times and locations across the top of the display. The intensity and contrast of the light was adjusted to a low enough value that foveation was necessary to detect its onset. Hence, this task simulated the visual attention demands of head up scanning. There were approximately 4 target

illuminations per trial, and each trial lasted approximately 90 seconds. This time, of course, was somewhat variable since it depended on the nature of the maneuver that the pilot selected. A counterbalanced within-subject design was used, so that each subject saw all three display types in a blocked order. The order viewed on day one was reversed on day 2.

Results: Experiment 3

The two measures of flight safety: actual conflicts and predicted conflicts, both yielded a monotonic increase in safety (reduction in the measure), as progressively more of the information features (intruder predictor, threat vector) were added. (Conflict: $F_{2,28}=3.01$; $p = .08$; Predicted conflict: $F_{2,28}=19.28$; $p < .01$). The reduction in conflict level, relative to the baseline, obtained by providing the intruder predictor, did not appear to be achieved by any substantial change in the nature of pilot maneuvers; only their accuracy. However, the further reduction in conflict level obtained by providing the threat vector appeared to be achieved by a significant increase in the amount of lateral maneuvering, as measured both by lateral stick (aileron) displacement ($F_{1,14}=3.20$; $p = .09$), by lateral deviations in the flight path ($F_{1,14}=3.16$; $p = .10$), and by the total time to complete the maneuver.

The effects on workload paralleled those on performance and hence were consistent with the second prediction outlined above, related to ecological interface design. That is, each augmentation systematically reduced the amount of workload. This reduction was greatest across the "mental demand" scale of the NASA TLX rating ($F_{2,28}=9.39$; $p < .01$).

Finally, our analysis failed to reveal any difference across the secondary task measure. Fuller details of the results may be found in Wickens and Morphew (1997).

Discussion: Experiment 3

The results of Experiment 3 clearly supported a pattern of effects consistent with the goals of our symbology design; that is to create predictive symbology that would perceptually represent information useful for conflict resolution, information which would otherwise need to be cognitively computed (at a resource cost), or poorly estimated (at a performance cost). At the same time, the results suggested that the costs of using all three display formats were non-trivial; the mean latency of secondary task detection was approximately 4 seconds, suggesting that a substantial amount of time was being spent head down. Furthermore, nearly 30% of the secondary signals were missed altogether. Naturally we would assume that this cost could be modulated if pilots had been given higher priority to the secondary task.. However, such a solution would likely degrade the ability to solve the conflict problem in a timely fashion; that is, the

perceptual and cognitive demands of free flight conflict avoidance are not trivial. In particular, the impact of such demands could be assumed to be substantial in single pilot operations.

Conclusion

In conclusion, the three studies reported here have employed a large sample of skilled GA pilots to help define how optimal traffic displays should be configured, to support either free flight or at least increased traffic awareness. We have shown how a range of performance and workload measures can provide insight into the ease of use of different display options, and into the qualitative characteristics of the control maneuvers that they encourage. Such data add only a small, but necessary component to the set of findings that must be established, before the viability of free flight can be ascertained.

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